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A Sustainable Technology to Produce Green and Clean Steel by Hydrogen Plasma Smelting Reduction

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Abstract - It is now widely acknowledged by the world that reduction in emissions of CO_2 gas to control global warming is of paramount importance. The CO_2 gas accumulated in the atmosphere absorbs and retains heat in the infrared range. One ppm of CO_2 concentration is equivalent to an addition to the atmosphere of approximately 7.8 $GtCO_2$ (Giga tons of carbon dioxide). The proposed draft of the National Steel Policy has forecast the country's steel-making capacity in the range of 244-281 million tons (MT) per annum by 2025. About 770 kg of coal is required to produce 1 ton of steel and therefore, it would require about 200 MT of coal to meet the target production by 2025. In the conventional process, 2.7 tons of CO_2 gas is generated per ton of crude steel production. These are staggering numbers, which call for the need to develop innovative and alternate method of steelmaking to replace the conventional method.

CSIR-IMMT, Bhubaneswar has developed a Hydrogen Plasma Smelting Reduction process in the laboratory scale to produce steel that completely eliminates CO_2 gas emission. It uses hydrogen gas as the source of heat energy to smelt iron ore in place of coke or coal that are used conventionally. Simultaneously, hydrogen is being looked upon as the future energy fuel that can be generated from water by using solar energy. The optimized laboratory scale parameters (hydrogen flow rate, argon flow rate, hydrogen volume, reduction time, feed rate and quantity) were replicated successfully in bench scale (10 kg) with the product obtained of 99.54% pure iron with negligible sulphur and phosphorous content.

Keywords – Hydrogen plasma; low-carbon steel; green and clean steel; sustainability

1. INTRODUCTION

Iron and steel sector is one of the vital yardsticks to India's economic growth and development. India's recent improvement in ranking to the second place amidst the world's top crude steel producing countries is a testimony to the fact that the demand and consumption of steel is all set to rise more in coming years. India targets to achieve 400 Mt steel production figure by 2040 [1]. The country's current per capita consumption of steel is only 74.1 kg when pitched against the world per capita consumption of 229.4 kg. As per the Steel authority, this figure is poised to reach 150 kg by end of 2025 [2]. However, the generation of greenhouse gases, especially the carbon dioxide and their release to the environment when steel is produced through combustion of coal in conventional process is quite a grave concern of researchers worldwide. At present, India produces 113 Mt of crude steel that is responsible for emission of 210 Mt of CO_2 along with other greenhouse gases to the atmosphere [3]. Going by this figure, when India will produce 400 Mt by 2040, it may generate 740 Mt of CO_2 along with other greenhouse gases which would make it a serious menace to the environment. There may be severe repercussions in the form of temperature rise as a result of drastic climate change that may have adverse impact on water supply and the entire ecosystem. The current work aims to contribute a solution to tackling this severe environmental pollution and also meeting the demand and consumption of steel by utilising a suitable and clean alternative reductant to coal such as hydrogen. The attempt to use hydrogen in plasma environment dates back to 1970s during which investigations on using thermal hydrogen plasma to reduce molten iron oxides were performed [4, 5]. There have been several developments evolving to address the need of hydrogen as a clean alternative to coal. For instance, POSCO has its indigenous program in place in which hydrogen-based steelmaking in FINEX process may be possible [6]. Similarly, hydrogen reduction of iron oxide in a flash reactor and molten oxide electrolysis were attempted in the USA at Utah university and MIT respectively [7, 8]. The most recent and the world's first development around commercialisation of hydrogen-based steelmaking was reported by Swedish steel maker Ovako Steel which introduce hydrogen heating in rolling mills, thereby curbing the carbon footprint from cradle to gate [9]. Walking along the same path, Primetals Technologies Limited, Austria has also developed a technology for reduction of iron ore by hydrogen with a forecast capacity of 250,000 tons of steel per year [10].

The current investigation covers a comprehensive study of using hydrogen as a promising and green reductant in plasma atmosphere. Plasma as the instant high energy source activates hydrogen which in turn becomes a strong reductant in its ionic form. As a result, reduction is fast and

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the molten iron produced is 99.54% pure with negligible percentage of phosphorous and sulphur in it, thus eliminating the need of additional unit processes, such as dephosphorisation and desulphurisation as followed in conventional steel making processes. The only by-product of this technology is water vapour which could easily be condensed and circulated in the system. Almost zero carbon content, presence of no impurities make the product green and clean steel as it is called. The effect of time, effect of hydrogen volume, and effect of iron ore feed quantity were all studied thoroughly before optimising the process parameters of this technological intervention.

2. HYDROGEN AND PLASMA

Hydrogen is a potential candidate for reduction of iron oxides, owing to its rapid reduction potential and also evolving water vapour as its only by-product during the combustion of iron oxides. Furthermore, its consumption is less when compared to carbon. Figure 1 shows the comparison of theoretical requirement of carbon and hydrogen when used as reductants to produce iron. Hydrogen required is considerably lower than that of carbon with the byproduct water vapour coming out of the process. For instance, to produce 112 tons of iron, carbon required is 35 tons as against only 6 tons of hydrogen.

Iron	C	H_2	CO	CO_2	H_2O
112	36		84		
112	18			66	
112		6			54

Fig. 1 Comparison of theoretical values of carbon and hydrogen when used as reductants

The only hindrance concerning the usage of hydrogen as a reducing agent is its limited supply and the associated cost. However, technologies are evolving to produce hydrogen cheaply from water and other green sources which will make hydrogen steelmaking a reality in future. Plasma, on the other hand, is an instant high-energy source that is kinetically stimulating. Plasma processing of iron oxides involves usage of non-thermal or cold plasma to produce directly reduced iron (DRI) from iron oxides and application of thermal plasma in smelting reduction of iron oxide to produce pig iron. The present work focuses on thermal plasma to reduce iron oxides by hydrogen. Also, in general, hydrogen is a strong reductant in its molecular form. However, the reduction potential of hydrogen increases exponentially when it is used in plasma environment. The hydrogen gas in plasma medium dissociates from molecular to atomic form and then from atomic to ionic form. It is worth noting that the reduction potential of atomic and ionic forms are 3 times and 15 times higher than that of the molecular hydrogen. So, these molecular, atomic, and ionic hydrogen make the hydrogen plasma smelting technology kinetically stimulating in nature.

3. METHODOLOGY AND EXPERIMENTAL

This one-step process of preparing clean and green steel (the flows sheet is represented in Figure 2) was performed in a state-of-the-art Hydrogen Plasma Smelting Reactor (HPSR) that supports up to 1kg scale of feed material. Both the schematic and actual images of the HPSR are shown in Figure 3. Argon gas was purged into the reactor chamber for initial 2 min at 10 litre per minute (LPM) to maintain a neutral atmosphere inside the chamber. Before passing the argon, iron ore fines in the form of granules were kept in the water-cooled copper crucible. Arcing was done to initiate plasma by maintaining a suitable distance between the tungsten tip of the plasma torch and the bath of the crucible. The first batch of iron ore was allowed to melt for 5 min after which the hydrogen gas was passed through the nozzle of the torch. During the course of the reduction process, the plasma torch was adjusted to position at different angles to attain uniformity in the reduction of iron oxides. The electromagnetic coil placed beneath the water-cooled copper crucible performed its duty of maintaining the agitation of the molten metal bath. The molten pool created was visible through the circular glass flange at the exterior side of the HPSR. Subsequently, different batches of iron ores in 50g scale were fed through the feeder to conduct and complete the reduction studies from 200g to 1000g scale.

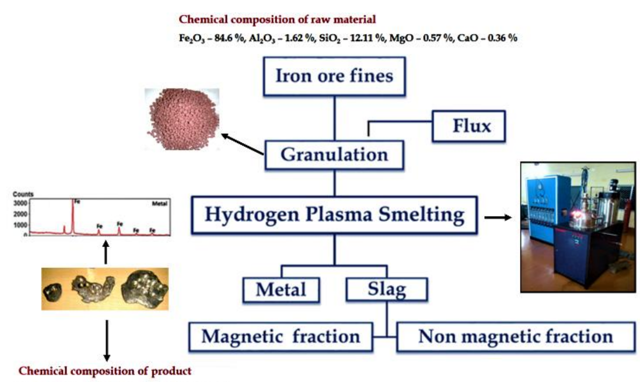

Fig. 2 Flow sheet of the one-step process of producing green and clean steel

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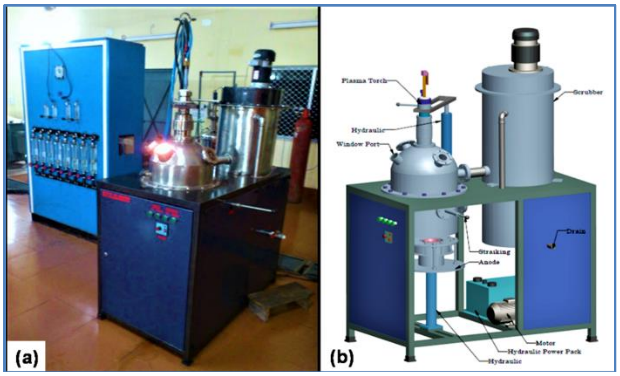

Fig. 3 (a) Real view and (b) schematic view of the HPSR

4. RESULTS AND DISCUSSION

To optimise the process parameters, time, hydrogen gas flow rate, and feed material quantity were varied to study their effect on reduction efficiency.

a. Effect of feed quantity

Usually, when a process gets scaled up, the reduction efficiency either increases or stays at a higher point. This similar behaviour was also observed when the feed quantity was increased from 200g to 1000g scale. It was also noted that the height of the bath increased with increased feed rate which must have bettered the reduction efficiency. The reduction percentage increased from 62% (200g scale) to 98% (1000g scale) which is highlighted in Table 1. The time of smelting reduction varied from 43 min to 244 min for different feed quantities to ensure the adequate supply of hydrogen. Each of the values against a specific feed quantity was arrived at after calculating the average of at least 5 sets of experiments.

TABLE I
Effect of feed quantity on reduction percentage
Ar: 10 LPM, H_2: 5 LPM, Feed rate: 50g/batch

Sl. No.	**Feed quantity (g)**	**Voltage (V)**	**Current (A)**	**Time (min)**	**Reduction (%)**
1	200	95	131	43	62.49
2	400	110	123	122	65.15
3	600	115	132	140	86.79
4	800	129	102	222	87.65
5	1000	106	121	244	98.14

b. Effect of hydrogen volume

After studying the effect of feed quantity on the reduction percentage, 1000g scale was chosen on which the hydrogen volume was varied to study its effect on extent of reduction. A series of five such experiments is presented in Table 2 in which hydrogen volume was varied from 800 litre to 1176 litre corresponding to their flow rates 6 LPM and 12 LPM respectively. As 10 LPM consumed 1020 litre of hydrogen with an achieved reduction of 99%, it was chosen as the idle parameter in this study.

TABLE II
Effect of hydrogen volume on reduction percentage
Ar: 10 LPM, Feed quantity: 1000g, Feed rate: 50g/batch

Sl. No.	**Hydrogen flow rate (LPM)**	**Time (min)**	**Hydrogen (L)**	**Voltage (V)**	**Current (A)**	**Reduction (%)**
1	5	222	1110	86	126	98.48
2	8	100	800	99	122	89.75
3	8	156	1248	105	121	99.50
4	10	102	1020	105	123	98.99
5	12	98	1176	110	124	99.10

c. Effect of time

With the feed quantity and hydrogen flow rate chosen as 1000g and 10 LPM respectively, a time variation study was performed to investigate its effect on reduction percentage. Table 3 presents the experimental data with the highest reduction percentage achieved when smelting reduction time was 102 min. The XRD spectra of the iron ore granules as feed material and the product obtained after 102 min are shown in Figures 4 and 5 respectively. The serial numbers 4 and 5 yielded a fused mass of metal and slag which resulted discrepancy in the reduction percentage.

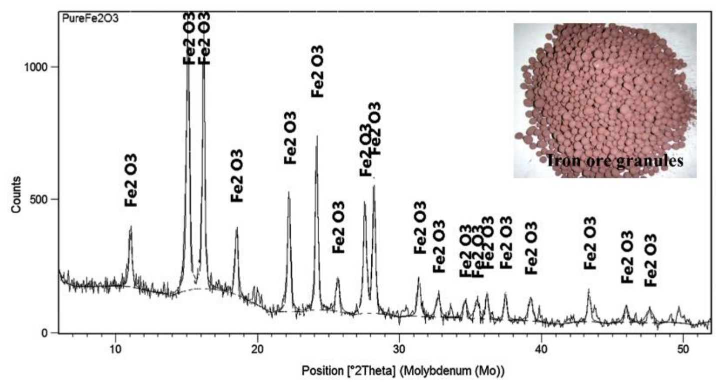

Fig. 4 Iron ore granules as the feed material and its XRD spectra

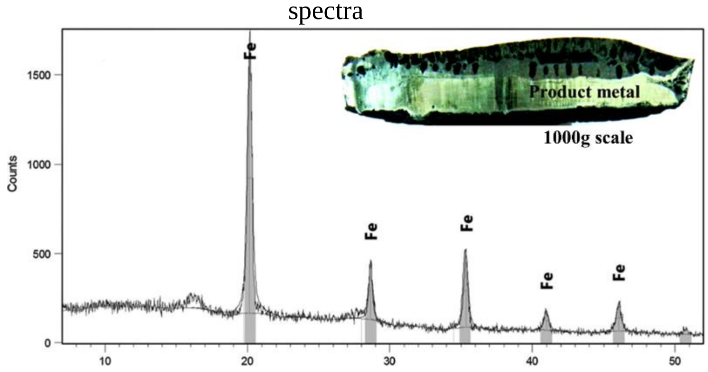

Fig. 5 Product metal and its XRD spectra

TABLE III
Effect of time on reduction percentage
Ar: 10 LPM, H2: 10 LPM, Feed quantity: 1000g, Feed rate: 50g/batch

Sl. No.	**Time (min)**	**Voltage (V)**	**Current (A)**	**Reduction (%)**
1	102	105	123	98.99
2	88	122	121	98.59
3	63	118	122	86.55
4	53	113	110	80.07
5	42	101	123	51.66

5. CONCLUSION

The following conclusions were arrived at from this one-step process of producing clean and green steel by HPSR technology:

(i) Almost 100% reduction was achieved by hydrogen smelting reduction of iron ore fines in the plasma environment.

(ii) The optimum process parameters were found to be reduction time (102 min), Ar flow rate and H_2 flow rate in 1:1 ratio for a feed quantity of 1000g with a feed rate of 50g per batch.

(iii) The only by-product is water vapour which makes this process environmentally friendly.

(iv) The metal contains only 0.02% phoshphorous and 0.007% sulphur which does not necessitate the additional refining operations, such as dephosphorisation and desulphurisation as followed in conventional steelmaking processes.

(v) Scaling up of the process will indicate the techno-economic feasibility for industry scale trials.

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